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THE PERFORMANCE OF 3500 MWth HOMOGENEOUS AND HETEROGENEOUS
METAL FUELED CORE DESIGNS

by

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ABSTRACT

Performance parameters are calculated for a representative 3500 MWth homogeneous and a heterogeneous metal fueled reactor design. The equilibrium cycle neutronic characteristics, safety coefficients, control system requirements, and control rod worths are evaluated. The thermal-hydraulic characteristics for both configurations are also compared. The heavy metal fuel loading requirements and neutronic performance characteristics are also evaluated for the uranium startup option.

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I. INTRODUCTION

The current metal fueled LMR core design studies have focused on cores with output in the 300-900 MWth range.¹⁻³ This range is perceived to be optimum under present and foreseeable U.S. socio-economic conditions. Traditionally, and especially under earlier projections of rapid growth in electrical demand, the optimum reactor size was expected to be in the 3000-4000 MWth range. To facilitate comparative studies of metal fueled LMRs at different sizes, the current study characterizes the performance parameters of two representative 3500 MWth size cores. The two representative cores are one which has a homogeneous configuration and a second which has a heterogeneous configuration. No attempt has been made to optimize the cores so as to take full advantage of the excellent neutronic properties of metal fuel. Rather, they are modeled after conventional oxide core configurations, and, in particular, the heterogeneous core configuration is modeled after the LSPB layout.

Although the core designs are not fully optimized, their neutronic performance characteristics, safety coefficients, control rod requirements and worths, will be sufficiently typical to allow for generalizations about the performance of large metal cores and for comparisons with large oxide fueled LMRs.

Detailed neutronic performance and safety characteristics are calculated and analyzed. Control system requirements are evaluated and control rod worths are determined. An analysis is made of the thermal-hydraulic characteristics of these cores. Due to the excellent neutron economy of metal fueled cores, there is an incentive to consider a startup with uranium rather than plutonium. The initial fissile requirements and neutronic performance characteristics of both configurations are calculated for uranium startup.

II. METAL CORE DESIGN DESCRIPTION

A general design description for the 3500 MWth/1200 MWe metal fueled reactors is given in Table I. The general reactor specifications are the same for both the homogenous and the heterogeneous designs. We note that the reactor outlet temperature of 950°F is slightly lower than that in many previous studies with oxide fueled cores. This choice of a lower temperature adds some conservatism due to the lack of data with respect to the high temperature behavior of HT-9 under irradiation. It is felt that a ferritic steel such as HT-9, which exhibits negligible irradiation induced swelling, is desirable due to the relatively high fast fluence associated with metal fueled cores.

The driver fuel residence time is assumed to be 3 cycles at an 80% capacity factor and a cycle length of 365 days for both cores. The internal blankets for the heterogeneous core also have a 3 cycle residence time, the same as for the driver assemblies. The radial blanket fuel for both cores has a 4 or 6 cycle residence time depending on the position of the assembly in the core. The fuel for the driver assemblies is mixed U-Pu-10% Zr while that for the blanket assemblies (both internal and radial) is U-10% Zr.

A. Homogeneous Core

The homogeneous core layout is shown in Figure 1. It has 414 driver assemblies which are divided into two enrichment zones so as to improve power peaking. The inner core zone has 222 driver assemblies and the outer core zone has 192. There are 37 control rods uniformly spaced with 19 in the inner core and 18 in the outer core. The choice of number of control rods, their in-core positioning, and their primary/secondary system assignments, are based on previous oxide studies and are likely not to be optimum for the metal fueled cores. The radial blanket has three rows of blanket assemblies for a total of 252 assemblies. The first row of 78 blanket assemblies has a 4 year residence and the second and third rows of 174 assemblies have a 6 year residence. The two row radial shield consists of 198 assemblies.

The homogenous core assembly design specifications are given in Table II and the core arrangement is described in Table III. The driver assemblies have a duct outside flat-to-flat of 6.287 inches with an assembly pitch of 6.454 inches. The structural material is HT-9. The duct wall thickness is 0.180 inches which results in a required interassembly gap of 0.167 inches. These dimensions were chosen to maximize the fuel volume fraction. The drivers consist of 271 fuel pins each with a fuel pin diameter of 0.300 inches and a pin pitch/diameter ratio of 1.18. The fuel pin diameter was chosen to achieve a 120 MWd/kg peak discharge burnup for a 3 cycle residence. The driver fuel is U-Pu-10% Zr with a smeared density of 75.0% and the cladding material is HT-9 with the thickness being 0.022 inches. The axial blanket fuel is U-10% Zr with an 85.0% smeared density. This axial blanket smear density may be too aggressive since smear density appears to be a critical parameter with respect to metal fuel lifetime.⁵ A more conservative approach (as taken on U.S. modular cores) is to set the smear density in the driver assembly axial blankets at 75%. This has little impact on burnup control swing.

In addition, due to the excellent breeding potential of cores with metallic fuel, the possibility exists for removing the axial blanket altogether. This core design option has been shown to be viable, even under conditions of a closed self-regenerative cycle with uranium startup.⁶ The removal of the axial blanket also simplifies the fuel reprocessing and can lead to a reduction in fuel cycle cost.

Figure 2 shows the homogeneous assembly design. The active driver length is 36 inches with 6 inch upper and lower blankets. The axial blanket thickness is estimated to give a low burnup swing. The upper fission gas plenum is 36 inches with the overall assembly length being 158 inches. The choice of a plenum-to-fuel length ratio of 1.0 is likely to accommodate the traditional design transients. The more recent approach to the inherent accommodation of long term transients has been to remove the heat directly through the primary system vessel, rather than through an auxiliary system. In the former approach equilibrium core temperatures are higher than in the latter and a plenum-to-fuel length ratio of 1.0 may not be sufficient. However, the efficiency of removing heat through the vessel in a 1000 MWe or greater system remains to be proven.

The radial blanket assembly has 169 fuel pins with a pin diameter of 0.415 inches. The fuel is U-10% Zr with an 85.0% smeared density and the structural and cladding material is HT-9 the same as for the driver assemblies. The blanket pin pitch/diameter is 1.082 and the active blanket length is 48.0 inches. The blanket design specifications are also given in Table II and shown in Figure 2.

B. Heterogeneous Core

The heterogeneous core layout is modeled after the Large Scale Prototype Breeder Reactor (LSPB)⁴ and is shown in Figure 3. The heterogeneous core assembly design specifications are also given in Table II and the core arrangement is described in Table III. The driver zone has 372 assemblies set in a heterogeneous pattern, a single enrichment zone, and a three year residence time. There are 175 internal blanket assemblies and 36 control rods. The radial blanket consists of an inner row of 90 assemblies having a 4 year residence and an outer row of 96 assemblies with a 6 year residence. Thus, the heterogeneous core has 2 rows of radial blankets compared to 3 rows for the homogeneous core.

The driver fuel is mixed U-Pu-10% Zr with 271 fuel pins per assembly. The fuel pin diameter is 0.285 inches with a smeared density of 75% and a pin pitch/diameter of 1.18. The fuel pin cladding thickness is 0.022 inches. The heterogeneous core pin size and duct wall thickness were the result of maximizing the fuel volume fraction. This results in an assembly outside flat-to-flat of 5.990 inches, a 0.180 inch duct wall thickness, and an interassembly gap of 0.160 inches. The active core height is 36 inches with 6 inch upper and lower axial blankets. The axial blanket fuel is U-10% Zr with a smeared density of 85%. The heterogeneous core assembly design is shown in Figure 4. The corresponding blanket design has 169 pins per assembly with a pin diameter of 0.392 inches and a cladding thickness of 0.030 inches. The blanket fuel is U-10% Zr with a smeared density of 85% and the blanket length is 48 inches. The blanket pin pitch/diameter ratio is 1.087.

These designs result in nearly identical total heavy metal inventories for the two cores - 88681 kg and 88360 kg respectively for the homogeneous and heterogeneous cores. The driver inventories are 36106 kg and 28752 kg respectively.

III. EQUILIBRIUM CYCLE NEUTRONIC PERFORMANCE

The equilibrium cycle neutronic performance of each core was calculated using the REBUS-3 fuel cycle code.⁷ The analysis used three dimensional hexagonal-z models and the nodal diffusion approach.⁸ A nine multi-group cross section set based on ENDF/B-V.2 nuclear data and consistent with these design parameters was used.⁹ Region dependent broad-group cross sections were generated using the MC²-2¹⁰ and SDX¹¹ cross section codes.

The homogeneous core performance and mass flow parameters are given in Table IV and the corresponding data for the heterogeneous core are given in Table V. The homogeneous design has a burnup reactivity swing of 0.53% Δk (BOEC-EOEC) while the heterogeneous design has a slight increase in

reactivity of -0.41% Δk . The homogeneous core has an initial fissile loading of 3965 kg and a driver heavy metal loading of 36106 kg. This results in an average fissile enrichment of 10.98%. The heterogeneous core has a fissile loading of 4673 kg and a driver heavy metal loading of 28753 kg which results in a 16.25% average fissile enrichment.

Table VI compares the equilibrium cycle fluxes and fluences for both cores. The homogeneous core experiences a slightly higher discharge fluence for the driver assemblies which is directly attributed to the slightly higher fluxes due to the lower enrichment when compared to the heterogeneous cores. The peak discharge fast fluence for the internal blankets of the heterogeneous core is about the same as for the driver assemblies. Table VII shows the peak nominal power densities for both cores. The peak power for the homogenous design ranges from 14.5 kW/ft at BOEC to 14.6 kW/ft at EOEC. Figures 5 through 8 show the peak power and peak flux by assembly for the homogenous design for both BOEC and EOEC. From these figures we can see that the peak power shift is from the outer core at BOEC to the inner core at EOEC. This leads to relatively flat power profile throughout life. The peak power ranges from 15.8 kW/ft at BOEC to 13.9 kW/ft at EOEC for the heterogeneous design. Figures 9 through 12 show the peak power and peak flux by assembly for the heterogeneous design at BOEC and EOEC. The peak power for the heterogeneous design is in a central core zone and remains there throughout the cycle. The peak internal blanket powers increase from 10.2 kW/ft to 13.9 kW/ft about the same level as the core.

The power fraction by region is shown in Table VIII. For the homogeneous design 93.2% of the power is in the core at BOEC with 3.0% and 3.5% respectively in the radial and axial blankets. At the EOEC there is a small build up in power in the blankets which results in 90.8% of the power in the core and 3.7% and 5.2% in the radial and axial blankets respectively. For the heterogeneous design only 80.7% of the power is produced by the core zone while 14.0% occurs in the internal blankets at BOEC. The radial and axial blankets have 3.0% and 1.9% respectively. By EOEC there is a substantial shift in power to the internal blankets resulting in 73.4% in the core, 20.2% in the internal blankets, 3.5% in the radial blankets, and 2.6% in the axial blankets.

The breeding characteristics and discharge burnups follow the patterns exhibited by the power shifts. Conversion and breeding ratios are given in Table IX. The majority of the homogenous design breeding occurs in the core zone with smaller contributions from the radial and axial blankets. The reactor breeding ratio is 1.205 which results in a 18.2 year compound system doubling time. The breeding characteristics for the heterogeneous design also correspond to the power production profiles with a major contribution coming from the internal blankets. The heterogeneous design breeding ratio is 1.248 and the compound system doubling time is 17.9 years which is nominally comparable to the homogeneous case.

The equilibrium cycle discharge burnups are given in Table X for both designs. For the homogeneous case the driver zone average discharge burnup is 76.8 MWd/kg and the peak discharge burnup is 115.2 MWd/kg. The peak burnup for the radial and axial blankets is 20.7 MWd/kg and 25.0 MWd/kg respectively. For the heterogeneous case the driver average discharge burnup is 81.3 MWd/kg with a peak discharge burnup of 132.2 MWd/kg. The

internal blankets reach a peak discharge burnup of 50.0 MWd/kg with the radial and axial blankets reaching 20.9 MWd/kg and 17.2 MWd/kg respectively.

IV. CONTROL SYSTEM PERFORMANCE

The control system requirements and control system assignments for both designs are given in Tables XI and XII. The homogeneous design has 37 control rods with 25 selected as the primary system and positioned in rows 1, 4, 7, and 11. There are 12 rods selected for the secondary system and they are evenly split between rows 7 and 11. The heterogeneous design has 36 control rods with 24 selected for the primary system and positioned in rows 5 and 13, and 12 rods are selected for the secondary system with all positioned in row 9. For the preliminary evaluations the primary and secondary rods utilize naturally enriched B_4C . The choices at control systems are not optimized and are based on experience with the design of large oxide fueled cores.

The maximum primary system requirement for the homogeneous design is 2.72% Δk and 1.30% Δk for the secondary system. The maximum primary system requirements for the heterogeneous design is 2.50% Δk and for the secondary system the maximum requirement is 1.27% Δk . The control system worths at BOEC are given in Table XIII and show that both the primary and secondary system worths are more than adequate to meet the requirements of both designs.

V. SAFETY CHARACTERISTICS

The safety coefficients were calculated for both designs for EOE conditions using the VARI-3D code¹² and the first order perturbation approximation. A 21 group cross section set was used to calculate the reactivity feedback coefficients and this set was consistent with the 9 group set used for the performance evaluations.⁹ The sodium void worth by zone and component is given in Table XIV. The homogeneous design has a 10.8 \$ void coefficient for the driver zone with smaller contributions coming from the radial and axial blankets. The heterogeneous design has a smaller 4.8 \$ void coefficient for the driver zone as would be expected. The void coefficient for the internal blankets is 2.73 \$ which gives a total of 7.5 \$ for both the driver and internal blankets. This is still lower than calculated for the homogeneous design. The delayed neutron data is given in Table XV and shows β_{eff} is 0.003434 and 0.003477 for the homogeneous and heterogeneous designs respectively.

A summary of the reactivity feedback coefficients is shown in Table XVI. The doppler coefficients are calculated for both flooded and for flowing sodium voided conditions. The flooded doppler for the homogeneous driver is 3.389×10^{-3} , 0.151×10^{-3} for the radial blanket, and 0.476×10^{-3} for the axial blanket. The corresponding voided doppler values are 1.640×10^{-3} for the driver, 0.102×10^{-3} for the radial blanket, and 0.330×10^{-3} for the axial blanket. For the heterogeneous case the flooded doppler coefficients are 1.552×10^{-3} for the driver, 1.795×10^{-3} for the internal blanket, 0.152×10^{-3} for the radial blanket, and 0.223×10^{-3} for the axial blanket. The corresponding voided doppler coefficients are 0.990×10^{-3} for

the driver, 1.310×10^{-3} for the internal blanket, 0.143×10^{-3} for the radial blanket, and 0.125×10^{-3} for the axial blanket. The radial expansion coefficient represents a uniform expansion of the core/radial blanket interface of 1 cm. It is -0.799 $\$/\text{cm}$ for the homogeneous case and -0.705 $\$/\text{cm}$ for the heterogeneous case. The axial expansion coefficient represents a uniform expansion of the driver zone of 1 cm for the homogeneous design and of the driver and internal blanket zones for the heterogeneous design. This results in a -0.233 $\$/\text{cm}$ axial expansion coefficient for the homogeneous case and a -0.202 $\$/\text{cm}$ expansion coefficient for the heterogeneous case.

VI. URANIUM STARTUP PERFORMANCE

The performance and mass flow characteristics for a uranium cycle startup were completed for both designs and are shown in Tables XVII and XVIII. These results represent the loading and discharge masses of a one batch cycle for a U-10Zr metal fueled core at 75% smear density. For the homogeneous design the initial fissile loading of the driver is 5805 kg of U-235 which gives a fissile enrichment of 16.1%. The reactivity burnup swing is 1.63% Δk and the breeding ratio is 0.846. The net buildup of Pu-239 is 870.1 kg at the expense of a loss of 1040.0 kg of U-235. The initial fissile loading for the heterogeneous design is 7157 kg of U-235 which gives a fissile enrichment of 24.9%. The effective breeding ratio is 0.865, and the net buildup of Pu-239 is 898.7 kg with a loss of U-235 of 1045.9 kg. The reactivity burnup swing is 0.60%.

VII. THERMAL-HYDRAULIC PERFORMANCE

The SE2-ANL code¹³ is used for the thermal-hydraulic analysis of the homogeneous and heterogeneous metal fueled designs. This code is a modified version of the SUPERENERGY-2 code¹⁴ which is widely used for LMFBR design analysis. The steady-state thermal-hydraulic analysis calculates the peak clad and coolant temperature profiles on an assembly by assembly basis for the BOEC and EOEC conditions. The orificing criteria equates the peak cladding 2- σ mid-wall temperatures for each orifice zone for the peak power condition at either BOEC or EOEC. For the heterogeneous core the driver assemblies are at their highest powers at BOEC and the blankets at EOEC. In the homogeneous core because of the two enrichment zones the peak driver powers can occur at either BOEC or EOEC while the radial blankets have their peak powers always at EOEC. The core flow orificing data for the homogeneous design is given in Table XIX and the assembly by assembly orifice zone assignments are shown in Figure 13. There are 7 driver orifice zones for the two enrichment homogeneous core, 6 for the radial blankets, and 1 each for the control rods and radial shield assemblies. The zone and assembly coolant flow rates, peak cladding 2- σ midwall temperatures, and the number of assemblies in each orificing zone for the homogeneous design are also given in Table XIX. The average peak 2- σ cladding midwall temperature for the homogeneous design over all orifice zones is 1150.6°F.

The core flow orificing data for the heterogeneous design is given in Table XX, and the assembly by assembly orifice zone assignments are shown in Figure 14. The driver assemblies are divided into 5 separate zones, the

internal blankets into 4 zones, the radial blankets also into 4 zones, and 1 zone each for the control rods and radial shield assemblies. The orificing criteria is the same as for the previous case in that the peak cladding 2- σ midwall temperatures are equated for all orifice zones over the entire burn cycle. The zone and assembly coolant flow rates, peak 2- σ clad midwall temperatures, and number of assemblies per orifice zone are given in Table XX. The assemblies are grouped for each orifice zone by peak total power and the flow rates for each zone are adjusted to equate the peak cladding temperatures. The average peak 2- σ cladding midwall temperature is 1203.1°F for all orifice zones. The 50°F higher cladding midwall temperatures experienced by the heterogeneous core compared to the homogeneous core are the result of the overcooling of the internal blanket assemblies at BOEC. The relatively large fraction of power generated by the internal blankets at EOEC requires a significant fraction of the total coolant flow which impacts the flow available at BOEC for the driver assemblies resulting in higher peak cladding temperatures at BOEC.

VIII. SUMMARY

The equilibrium cycle neutronic performance parameters were calculated for both the homogeneous and heterogeneous designs. The homogeneous design has a relatively low burnup reactivity swing of 0.53% Δk (BOEC-EOEC) while the heterogeneous design has a slight increase in reactivity over the cycle of -0.41% Δk . Both designs have similar heavy metal loading requirements, but the heterogeneous design has a higher effective fissile enrichment of 16.25% compared to 10.98% for the homogeneous case. The peak power for the homogeneous case ranges from 14.5 kW/ft at BOEC in the outer core to 14.6 kW/ft at EOEC in the inner core which leads to a relatively flat power profile throughout life. The peak powers for the heterogeneous design range from 15.8 kW/ft at BOEC to 13.9 kW/ft at EOEC and remain in the central fuel zones throughout the cycle. The peak internal blanket powers increase from 10.3 kW/ft to 13.9 kW/ft which is at about the same levels as for the drivers.

The reactor breeding ratio is 1.205 for the homogeneous case with a 18.2 year compound system doubling time and 1.248 for the heterogeneous case with a 17.9 year compound system doubling time. The average discharge burnup for the homogeneous driver assemblies is 76.8 MWd/kg with a peak discharge burnup of 115.2 MWd/kg. For the heterogeneous case the driver average discharge burnup is 81.3 MWd/kg and the peak discharge burnup is 132.2 MWd/kg. Because of the low cycle reactivity burnup swings the primary and secondary control requirements are quite low. These are met for both cores with naturally enriched B₄C control rods.

The safety and reactivity feedback coefficients were calculated for both designs for EOEC conditions. The homogeneous case has a relatively high sodium void worth of 10.8 \$ for the driver assemblies with smaller contributions coming from the radial and axial blankets. The heterogeneous case has a smaller 4.8 \$ void coefficient for the drivers and a 2.73 \$ value₃ for the internal blankets. The flooded doppler coefficients are 3.389×10^{-3} for the homogeneous driver assemblies and 1.552×10^{-3} and 1.795×10^{-3} for the heterogeneous driver and internal blankets respectively. The radial and axial expansion coefficients are similar for both designs.

The performance and mass flow characteristics for a uranium cycle startup were calculated for each case. The homogeneous case has an effective driver enrichment of 16.1% and a fissile loading requirement of 5805 kg of U-235. The effective enrichment for the heterogeneous case is 24.9% which results in a 24% higher fissile loading of 7157 kg of U-235. The SE2-ANL code was used to calculate peak cladding and coolant temperature profiles for both cases at BOEC and EOEC conditions. The average peak 2- σ cladding midwall temperature over all orifice zones is 1150.6°F for the homogeneous case and 1203.1°F for the heterogeneous case.

IX. ACKNOWLEDGMENTS

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Figure 1. Homogeneous Metal Reactor Layout

Figure 2. Homogeneous Metal Assembly Design

Figure 3. Heterogeneous Metal Reactor Layout

Figure 4. Heterogeneous Metal Assembly Design

Figure 5. Homogeneous Core BOEC Peak Power Density (kW/l)

Figure 6. Homogeneous Core EOEC Peak Power Density (kW/l)

Figure 7. Homogeneous Core BOEC Peak Flux ($\times 10^{15} \text{n/cm}^2\text{-sec}$)

Figure 8. Homogeneous Core EOEC Peak Flux ($\times 10^{15} \text{n/cm}^2\text{-sec}$)

Figure 9. Heterogeneous Core BOEC Peak Power Density (kW/l)

Figure 10. Heterogeneous Core EOEC Peak Power Density (kW/l)

Figure 11. Heterogeneous Core BOEC Peak Flux ($\times 10^{15} \text{ n/cm}^2\text{-sec}$)

Figure 12. Heterogeneous Core EOEC Peak Flux ($\times 10^{15} \text{ n/cm}^2\text{-sec}$)

Figure 13. Homogeneous Core Orificing Zone Assignment

Figure 14. Heterogeneous Core Orificing Zone Assignment

TABLE I
Reactor Design Specifications

	<u>Homogeneous</u>	<u>Heterogeneous</u>
General		
Reactor Power, MWth	3500	3500
Core Concept	Homogeneous	Heterogeneous
Primary Na Outlet Temperature, ° F	950	950
Primary Na Inlet Temperature, ° F	670	670
Reactor ΔT , ° F	280	280
Fuel Residence Time, Cycles		
Driver	3	3
Internal Blankets	-	3
Radial Blankets	4/6	4/6
Core Structural Material	HT-9	HT-9
Cycle Length, days	365	365
Capacity Factor, %	80	80
Reactor Core Arrangement		
Hexagonal Lattice Pitch, in	6.454	6.150
Number of Assemblies		
Driver	414	372
Internal Blanket	-	175
Radial Blanket	252	186
Control Rod	37	36
Radial Reflector	198	324
Active Core Height, in	36	36
Axial Blanket Thickness, in	6	6
Driver Enrichment Zones	2	1

TABLE II
Assembly Design Specifications

	<u>Homogeneous</u>	<u>Heterogeneous</u>
Driver Assembly		
Fuel	(U-Pu)Zr	(U-Pu)Zr
Cladding and Duct Material	HT-9	HT-9
Number of Pins per Assembly	271	271
Fuel Pin Diameter, in	0.300	0.285
Cladding Thickness, in	0.022	0.022
Pitch/Diameter Ratio	1.18	1.18
Fuel Smear Density, %T.D.	75.0	75.0
Active Fuel Length, in	36.0	36.0
Axial Blanket Thickness, in	6.0	6.0
Assembly Lattice Pitch, in	6.454	6.150
Duct Outside Flat-to-Flat, in	6.287	5.990
Duct Wall Thickness, in	0.180	0.180
Interassembly Gap, in	0.167	0.160
Blanket Assembly		
Fuel	U-Zr	U-Zr
Cladding and Duct Material	HT-9	HT-9
Number of Pins per Assembly	169	169
Fuel Pin Diameter, in	0.415	0.392
Cladding Thickness, in	0.032	0.030
Pitch/Diameter Ratio	1.082	1.087
Smear Density, %T.D.	85.0	85.0
Blanket Length, in	48.0	48.0
Assembly Lattice Pitch, in	6.454	6.150
Duct Outside Flat-to-Flat, in	6.287	5.990
Duct Wall Thickness, in	0.180	0.180
Interassembly Gap, in	0.167	0.160

TABLE III
Core Arrangement

	Number of Assemblies	
	<u>Homogeneous</u>	<u>Heterogeneous</u>
Driver	414	372
Internal Blankets	-	175
Radial Blankets	252	186
Control Rods	37	36
Radial Reflectors	198	324
Total	901	1093

TABLE IV

Homogeneous Reactor Performance and Mass Flow Data

										BREEDING RATIO	POWER SPLIT	SPEC. POWER KWTH/KGHH	BURNUP MWD/KG
REACTOR POWER, MWE/MWTH				: 1300/3500		CORE		0.847	92.464	89.631	78.517		
FUEL RESIDENCE TIME, FPD				: 3 X 292		AX.BLANKET		0.176	4.420	11.342	9.935		
CAPACITY FACTOR, %				: 80		RD.BLANKET		0.097	2.145	6.231	7.277		
BOC KEFF - EOC KEFF				: 5.287E-03		O.RD. BLANKET		0.084	0.971	1.264	2.215		
COMPOUND SYSTEM DOUBLING TIME, YRS				: 18.2		REACTOR TOTAL		1.205	100.000				
	U-235	U-236	U-238	PU238	PU239	PU240	PU241	PU242	TOTAL FISSILE	TOTAL HM			
INITIAL													
LOADING,KG													
CORE	62.2	0.0	31454.2	0.5	3914.2	618.1	51.3	5.6	3965.5	36106.1			
AX.BLANKET	27.3	0.0	13612.7	0.0	0.0	0.0	0.0	0.0	0.0	13640.0			
RD.BLANKET	24.1	0.0	12027.2	0.0	0.0	0.0	0.0	0.0	0.0	12051.3			
O.RD.BLKT.	53.8	0.0	26829.9	0.0	0.0	0.0	0.0	0.0	0.0	26883.6			
TOTAL	167.4	0.0	83924.0	0.5	3914.2	618.1	51.3	5.6	3965.5	88681.0			
EQUILIBRIUM													
LOADING,KG/YR													
CORE	20.7	0.0	10484.7	0.2	1304.7	206.0	17.1	1.9	1321.8	12035.4			
AX.BLANKET	9.1	0.0	4537.6	0.0	0.0	0.0	0.0	0.0	0.0	4546.7			
RD.BLANKET	6.0	0.0	3006.8	0.0	0.0	0.0	0.0	0.0	0.0	3012.8			
O.RD.BLKT.	9.0	0.0	4471.6	0.0	0.0	0.0	0.0	0.0	0.0	4480.6			
TOTAL	44.8	0.0	22500.7	0.2	1304.7	206.0	17.1	1.9	1321.8	24075.4			
EQUILIBRIUM													
DISCHARGE,KG/YR													
CORE	9.9	2.0	9506.7	0.2	1217.9	284.9	28.9	4.2	1246.8	11054.8			
AX.BLANKET	6.3	0.6	4343.8	0.0	147.7	6.7	0.3	0.0	147.9	4505.4			
RD.BLANKET	4.4	0.3	2898.9	0.0	85.5	2.8	0.1	0.0	85.6	2992.1			
O.RD.BLKT.	7.6	0.3	4334.0	0.0	77.6	1.3	0.0	0.0	77.7	4471.4			
TOTAL	28.2	3.3	21133.4	0.2	1523.7	296.2	29.3	4.2	1558.0	23023.5			
NET GAIN,KG/YR													
CORE	-10.8	2.0	-978.0	0.0	-86.8	78.9	11.8	2.3	-75.0	-980.6			
AX.BLANKET	-2.8	0.6	-193.8	0.0	147.7	6.7	0.3	0.0	147.9	-41.3			
RD.BLANKET	-1.6	0.3	-107.9	0.0	85.5	2.8	0.1	0.0	85.6	-20.8			
O.RD.BLKT.	-1.4	0.3	-87.6	0.0	77.6	1.3	0.0	0.0	77.7	-9.2			
TOTAL	-16.6	3.3	-1367.4	0.0	224.0	90.2	12.2	2.3	236.2	-1051.9			

- NOTE : 1. FISSILE = PA233 + U233 + PU239 + PU241
 2. BR AND CSDT CALCULATED WITH EQUAL FISSILE ISOTOPE WEIGHTING AND CREDIT FOR PA-233
 3. CSDT CALCULATED WITH 1-YEAR EXTERNAL CYCLE TIME AND 1% REPROCESSING/FABRICATION LOSSES
 4. EQUILIBRIUM LOADING AND DISCHARGE DATA ARE GIVEN IN TERMS OF EQUIVALENT ANNUAL MASS FLOW

Heterogeneous Reactor Performance and Mass Flow Data

NOTE: 1. FISSILE = PA233 + U233 + PU239 + PU241
2. BR AND CSOT CALCULATED WITH EQUAL FISSILE ISOTOPE WEIGHTING AND CREDIT FOR PA-233
3. CSOT CALCULATED WITH 1-YEAR EXTERNAL CYCLE TIME AND 1% REPROCESSING/FABRICATION LOSSES
4. EQUILIBRIUM LOADING AND DISCHARGE DATA ARE GIVEN IN TERMS OF EQUIVALENT ANNUAL FUEL FLOW

TABLE VI
Equilibrium Cycle Fluxes and Fluences

	<u>Peak Flux</u> ($10^{15}\text{cm}^{-2}\text{sec}^{-1}$)		<u>Peak Fast Flux</u> ($10^{15}\text{cm}^{-2}\text{sec}^{-1}$)		<u>Peak Fast Fluence</u> (10^{23}cm^{-2})
	BOEC	EOEC	BOEC	EOEC	
<u>Homogeneous</u>					
Driver	7.61	8.01	4.87	5.15	3.79
Radial Blanket	3.25	3.09	1.40	1.37	1.40
Axial Blanket	4.08	4.51	1.92	2.22	1.57
<u>Heterogeneous</u>					
Driver	6.99	6.88	4.73	4.64	3.58
Internal Blanket	6.94	6.85	4.47	4.45	3.39
Radial Blanket	3.24	2.96	1.56	1.44	1.57
Axial Blanket	3.46	3.60	1.71	1.81	1.33

TABLE VII
Peak Nominal Power Densities (kW/liter / kW/ft)

	<u>Homogeneous</u>		<u>Heterogeneous</u>	
	BOEC	EOEC	BOEC	EOEC
Driver	552.6/14.5	558.9/14.6	663.6/15.8	586.2/13.9
Internal Blankets	-	-	268.6/10.2	365.6/13.9
Radial Blankets	98.4/ 4.13	114.5/ 4.81	101.1/ 3.85	109.2/ 4.16
Axial Blankets	111.8/ 2.93	174.6/ 4.57	72.7/ 1.73	101.8/ 2.42

TABLE VIII
Equilibrium Cycle Power Fractions

	<u>Homogeneous</u>		<u>Heterogeneous</u>	
	BOEC	EOEC	BOEC	EOEC
Driver	93.15	90.77	80.73	73.38
Internal Blankets	-	-	14.00	20.15
Radial Blankets	2.97	3.70	3.00	3.48
Axial Blankets	3.52	5.16	1.86	2.57

TABLE IX
Equilibrium Cycle Breeding Parameters

	<u>Homogeneous</u>		<u>Heterogeneous</u>	
	Conversion Ratio	Breeding Ratio	Conversion Ratio	Breeding Ratio
Driver	0.9075	0.8474	0.6263	0.5033
Internal Blanket	-	-	3.2031	0.4875
Radial Blanket	6.7177	0.1811	6.0994	0.1567
Axial Blanket	4.4953	0.1765	5.4220	0.1005
Reactor Total		1.2051		1.2480

TABLE X
Equilibrium Cycle Discharge Burnup (MWd/kg)

	<u>Homogeneous</u>		<u>Heterogeneous</u>	
	Average	Peak	Average	Peak
Driver	76.75	115.19	81.34	132.23
Internal Blanket	-	-	20.26	50.01
Radial Blanket	3.87	20.73	5.15	20.90
Axial Blanket	8.72	24.98	6.23	17.24

TABLE XI
Estimate of Control System Requirements

	<u>Homogeneous</u>		<u>Heterogeneous</u>	
	Primary System, % Δk	Secondary System, % Δk	Primary System, % Δk	Secondary System, % Δk
Hot to Cold ^a	0.49	0.30	0.45	0.27
Reactivity Fault ^b / Shutdown Margin ^c	0.05 1.00	0.05 1.00	0.09 1.00	0.09 1.00
Reactivity Excess ^d	0.81		0.64	
Criticality Uncertainty ^e	± 0.30		± 0.30	
Fissile Tolerance ^f	± 0.29		± 0.28	
Total Requirement	2.30 $\pm$ 0.42	1.30	2.09 $\pm$ 0.41	1.27
Maximum Requirement	2.72	1.30	2.50	1.27

^aDetermined from the total reactivity increase associated with a decrease in temperature from operating temperature (800 ° K) to refueling temperature (477 ° K) for primary system or to hot standby temperature (588 ° K) for secondary system. Values shown are 20% greater than nominal values to account for uncertainties.

^bBased on runout from a maximum insertion depth at BOEC of a row-7 flat control rod for the homogeneous design and a row-5 corner control rod for the heterogeneous design with a rod interaction factor of 1.5.

^cA shutdown margin of 1.0 % ΔK is used because it exceeds the rod runout worth.

^dDetermined from 1.15 * (burnup reactivity swing) + 0.2% ΔK .

^eAssumed equal to CRBR values.

^fBased on an uncertainty of 0.5% in batch fissile enrichments.

TABLE XII
Control System Assignment

<u>Homogeneous</u> <u>Number of Rods</u>		<u>Heterogeneous</u> <u>Number of Rods</u>	
Primary System	Secondary System	Primary System	Secondary System
Row 1	1	Row 5	6
Row 4	6	Row 9	12
Row 7	6	Row 13	18
Row 11	12		
Total	25		24
	12		12

TABLE XIII
Control System Worths at BOEC (% Δk)

	<u>Homogeneous</u>		<u>Heterogeneous</u>	
	Primary System	Secondary System	Primary System	Secondary System
Total Worth	5.425	2.713	3.235	2.166
Stuck Rod Worth	0.532	0.535	0.408	0.396
Minimum Worth	4.893	2.178	2.827	1.770

For both cores the primary and secondary control rods use 19.8 % B₄C.

TABLE XIV
Sodium Void Worth (\$)

	<u>Spectral</u> ^a	<u>Leakage</u>	<u>Capture</u>	<u>Total</u>
<u>Homogeneous</u>				
Driver	13.534	-3.374	0.655	10.814
Radial Blanket	0.326	-0.337	0.014	0.003
Axial Blanket	1.002	-1.290	0.041	-0.246
<u>Heterogeneous</u>				
Driver	6.372	-1.899	0.337	4.811
Internal Blanket	3.195	-0.634	0.166	2.727
Radial Blanket	0.262	-0.272	0.013	0.003
Axial Blanket	0.497	-0.773	0.020	-0.255

^aAccounts for the increase in the average neutron energy due to the decrease in neutron moderation upon the loss of sodium.

TABLE XV
Delayed Neutron Data

Family	Homogeneous		Heterogeneous	
	β_i	$\lambda_i(s^{-1})$	β_i	$\lambda_i(s^{-1})$
1	7.9279-5	1.2988-2	7.9566-5	1.2990-2
2	7.1657-4	3.1429-2	7.2046-4	3.1447-2
3	6.3284-4	1.3575-1	6.3879-4	1.3581-1
4	1.2399-3	3.4698-1	1.2569-3	3.4717-1
5	5.7835-4	1.3734+0	5.8909-4	1.3736+0
6	1.8757-4	3.7737+0	1.9172-4	3.7811+0
β_{eff}	3.4345-3		3.4765-3	
$l_p(s)$	3.0817-7		2.8064-7	

TABLE XVI
Reactivity Feedback Coefficients

	<u>Homogeneous</u>	<u>Heterogeneous</u>
Sodium Void, \$		
Driver	10.814	4.811
Internal Blanket		2.727
Radial Blanket	0.003	0.003
Axial Blanket	-0.246	-0.255
Fuel Doppler Coefficient, $\times 10^{-3}$ (-Tdk/dT)		
Flooded Doppler		
Driver	3.389	1.552
Internal Blanket		1.795
Radial Blanket	0.151	0.152
Axial Blanket	0.476	0.223
Voided Doppler		
Driver	1.640	0.990
Internal Blanket		1.310
Radial Blanket	0.102	0.143
Axial Blanket	0.330	0.125
Radial Expansion Coefficient, \$/cm	-0.799	-0.705
Axial Expansion Coefficient, \$/cm	-0.233	-0.202
Beta-Effective, $\times 10^{-3}$	3.435	3.477
Prompt Neutron Lifetime, $\times 10^{-7}$ s	3.082	2.806

TABLE XVII

**Homogeneous Core Uranium Startup
Reactor Performance and Mass Flow Data**

						BREEDING RATIO	POWER SPLIT	SPEC. POWER KWTH/KGHW	BURNUP MWD/KG
REACTOR POWER, MWE/MWTH	: 1300/3500	CORE	0.584	96.521	93.564	27.321			
FUEL RESIDENCE TIME, FPD	: 1 X 292	AX.BLANKET	0.133	2.216	5.686	1.660			
CAPACITY FACTOR, %	: 80	RD.BLANKET	0.071	0.972	2.822	0.824			
		O.RD. BLANKET	0.059	0.291	0.379	0.111			
BOC KEFF - EOC KEFF	: 1.632E-02	REACTOR TOTAL	0.846	100.000					
COMPOUND SYSTEM DOUBLING TIME, YRS	: 0.0								
	U-235	U-236	U-238	PU239	PU240	PU241	TOTAL FISSILE	TOTAL HM	
INITIAL LOADING,KG									
CORE	5804.5	0.0	30301.6	0.0	0.0	0.0	0.0	36106.1	
AX.BLANKET	27.3	0.0	13612.7	0.0	0.0	0.0	0.0	13640.0	
RD.BLANKET	24.1	0.0	12027.2	0.0	0.0	0.0	0.0	12051.3	
O.RD.BLKT.	53.8	0.0	26829.9	0.0	0.0	0.0	0.0	26883.6	
TOTAL	5909.6	0.0	82771.4	0.0	0.0	0.0	0.0	88681.0	
EQUILIBRIUM LOADING,KG/YR									
CORE	5804.5	0.0	30301.6	0.0	0.0	0.0	0.0	36106.1	
AX.BLANKET	27.3	0.0	13612.7	0.0	0.0	0.0	0.0	13640.0	
RD.BLANKET	24.1	0.0	12027.2	0.0	0.0	0.0	0.0	12051.3	
O.RD.BLKT.	53.8	0.0	26829.9	0.0	0.0	0.0	0.0	26883.6	
TOTAL	5909.6	0.0	82771.3	0.0	0.0	0.0	0.0	88680.9	
EQUILIBRIUM DISCHARGE,KG/YR									
CORE	4769.7	203.1	29518.7	587.6	9.9	0.1	587.8	35089.2	
AX.BLANKET	24.6	0.6	13453.4	140.4	1.7	0.0	140.5	13620.8	
RD.BLANKET	22.7	0.3	11942.1	77.0	0.5	0.0	77.0	12042.5	
O.RD.BLKT.	52.6	0.3	26763.2	65.0	0.2	0.0	65.0	26881.3	
TOTAL	4869.6	204.3	81677.2	870.1	12.4	0.2	870.2	87633.7	
NET GAIN,KG/YR									
CORE	-1034.8	203.1	-782.9	587.6	9.9	0.1	587.8	-1016.9	
AX.BLANKET	-2.7	0.6	-159.4	140.4	1.7	0.0	140.5	-19.2	
RD.BLANKET	-1.4	0.3	-85.1	77.0	0.5	0.0	77.0	-8.7	
O.RD.BLKT.	-1.2	0.3	-66.7	65.0	0.2	0.0	65.0	-2.4	
TOTAL	-1040.0	204.3	-1094.1	870.1	12.4	0.2	870.2	-1047.2	

NOTE : 1. FISSILE = PA233 + U233 + PU239 + PU241

2. BR AND CSDT CALCULATED WITH EQUAL FISSILE ISOTOPE WEIGHTING AND CREDIT FOR PA-233

3. CSDT CALCULATED WITH 1-YEAR EXTERNAL CYCLE TIME AND 1% REPROCESSING/FABRICATION LOSSES

4. EQUILIBRIUM LOADING AND DISCHARGE DATA ARE GIVEN IN TERMS OF EQUIVALENT ANNUAL MASS FLOW

TABLE XVIII

**Heterogeneous Core Uranium Startup
Reactor Performance and Mass Flow Data**

							BREEDING RATIO	POWER SPLIT	SPEC. POWER KWTH/KGHW	BURNUP MWD/KG
REACTOR POWER, MWE/MWTH	: 1300/3500	CORE	0.315	87.562	106.613	31.131				
FUEL RESIDENCE TIME, FPD	: 1 X 292	INT. BLANKET	0.350	9.769	14.100	4.117				
CAPACITY FACTOR, %	: 80	AX. BLANKET	0.074	1.217	4.444	1.298				
		RD. BLANKET	0.070	1.121	3.152	0.920				
		O. RD. BLANKET	0.044	0.308	0.811	0.237				
BOC KEFF - EOC KEFF	: 5.920E-03	REACTOR TOTAL	0.855	100.000						
COMPOUND SYSTEM DOUBLING TIME, YRS	: 0.0									
	U-235	U-236	U-238	Pu239	Pu240	Pu241	TOTAL FISSILE	TOTAL - HM		
INITIAL LOADING, KG										
CORE	7156.6	0.0	21595.9	0.0	0.0	0.0	0.0	28752.5		
IN. BLANKET	48.5	0.0	24201.3	0.0	0.0	0.0	0.0	24249.8		
AX. BLANKET	19.2	0.0	9565.0	0.0	0.0	0.0	0.0	9584.2		
RD. BLANKET	24.9	0.0	12446.4	0.0	0.0	0.0	0.0	12471.3		
O. RD. BLKT.	26.6	0.0	13276.1	0.0	0.0	0.0	0.0	13302.7		
TOTAL	7275.8	0.0	81084.5	0.0	0.0	0.0	0.0	88360.4		
EQUILIBRIUM LOADING, KG/YR										
CORE	7156.6	0.0	21595.9	0.0	0.0	0.0	0.0	28752.5		
IN. BLANKET	48.5	0.0	24201.2	0.0	0.0	0.0	0.0	24249.7		
AX. BLANKET	19.2	0.0	9565.0	0.0	0.0	0.0	0.0	9584.2		
RD. BLANKET	24.9	0.0	12446.4	0.0	0.0	0.0	0.0	12471.3		
O. RD. BLKT.	26.6	0.0	13276.1	0.0	0.0	0.0	0.0	13302.7		
TOTAL	7275.8	0.0	81084.5	0.0	0.0	0.0	0.0	88360.4		
EQUILIBRIUM DISCHARGE, KG/YR										
CORE	6121.5	197.3	21163.8	323.3	4.0	0.0	323.3	27809.9		
IN. BLANKET	41.7	1.4	23751.7	370.0	5.0	0.1	370.0	24168.8		
AX. BLANKET	17.7	0.3	9576.4	78.7	0.8	0.0	78.7	9573.9		
RD. BLANKET	23.5	0.3	12360.7	76.4	0.4	0.0	76.4	12461.3		
O. RD. BLKT.	25.7	0.2	13223.8	50.4	0.2	0.0	50.4	13300.3		
TOTAL	6229.9	199.6	79976.4	898.7	10.4	0.1	898.8	87315.2		
NET GAIN, KG/YR										
CORE	-1035.2	197.3	-432.0	323.3	4.0	0.0	323.3	-942.6		
IN. BLANKET	-6.8	1.4	-449.5	370.0	5.0	0.1	370.0	-79.9		
AX. BLANKET	-1.5	0.3	-88.5	78.7	0.8	0.0	78.7	-10.2		
RD. BLANKET	-1.4	0.3	-85.7	76.4	0.4	0.0	76.4	-9.9		
O. RD. BLKT.	-0.9	0.2	-52.3	50.4	0.2	0.0	50.4	-2.4		
TOTAL	-1045.9	199.6	-1108.1	898.7	10.4	0.1	898.8	-1045.1		

NOTE : 1. FISSILE = PA233 + U233 + PU239 + PU241

2. BR AND CSST CALCULATED WITH EQUAL FISSILE ISOTOPE WEIGHTING AND CREDIT FOR PA-233

3. CSST CALCULATED WITH 1-YEAR EXTERNAL CYCLE TIME AND 1% REPROCESSING/FABRICATION LOSSES

4. EQUILIBRIUM LOADING AND DISCHARGE DATA ARE GIVEN IN TERMS OF EQUIVALENT ANNUAL MASS FLOW

TABLE XIX
Homogeneous Core Flow Orificing Data

Zone	Assembly Type	Number of Assemblies	Total Flowrate 10 ⁶ lbm/hr	Flow/Assembly lbm/hr	Peak 2- σ Clad Midwall Temp ° F
1	D	78	28.235	361989	1160.2
2	D	84	27.874	331829	1164.7
3	D	60	18.436	307267	1160.3
4	D	30	10.214	340456	1156.3
5	D	36	11.244	312345	1157.9
6	D	54	15.163	280801	1147.5
7	D	72	16.772	232949	1146.9
8	RB	60	4.152	69199	1143.4
9	RB	18	0.844	46885	1146.4
10	RB	54	1.384	25626	1146.4
11	RB	30	0.564	18812	1139.7
12	RB	60	0.476	7937	1144.9
13	RB	30	0.150	4991	1142.8
14	CR	37	TBD	TBD	
15	Shield	198	TBD	TBD	
Total		901	135.875		

TABLE XX
Heterogeneous Core Flow Orificing Data

Zone	Assembly Type	Number of Assemblies	Total Flowrate 10⁶ lbm/hr	Flow/Assembly lbm/hr	Peak 2- σ Clad Midwall Temp ° F
1	D	108	38.088	352666	1200.6
2	D	66	19.077	289045	1201.1
3	D	84	19.992	237998	1201.6
4	D	60	12.147	202452	1201.7
5	D	54	9.726	180115	1202.2
6	IB	36	8.216	228227	1205.9
7	IB	48	9.259	192904	1204.7
8	IB	30	4.300	143321	1206.3
9	IB	61	8.154	133670	1203.4
10	RB	66	3.685	55835	1195.6
11	RB	24	0.824	34344	1209.2
12	RB	72	1.658	23034	1199.5
13	RB	24	0.321	13377	1208.8
14	CR	36	TBD	TBD	
15	Shield	324	TBD	TBD	
Total		1093	135.864		